Smart Sampling

A Tutorial:

A real-life adventure in environmental decision making

**The U. S. Department of Energy's Mound Plant
Miamisburg, Ohio**

Sandia National Laboratories

Smart Sampling

Purpose:

This is a tutorial on risk assessment for environmental remediation. It has been prepared to introduce the basic concepts of

- **Economic risk assessment**
- **Probabilistic risk assessment**
- **Geostatistical simulation**
- **Environmental decision making**

We will follow a project called SmartSampling through a real problem. The tutorial is divided into six sections that correspond to the real sequence of events.

- **Problem definition**
- **Building an economic objective function**
- **Understanding the economic risk term**
- **Characterization and sampling**
- **Quantifying geologic uncertainty**
- **Evaluating economic trade-offs**

A section that contains links to related web sites and resources available over the web is provided at the end of the tutorial.

Problem Definition

In this section we start answering the very basic questions of an environmental remediation: who, what, and where?

Where: The Miami-Erie Barge Canal Adjacent to the U.S. Department of Energy's Mound Plant in Miamisburg, Ohio

The Mound plant was an integrated research, development, and weapons production facility. The plant is located within the city limits of Miamisburg in southwestern Ohio and occupies 306 acres. The site sits on a bluff overlooking the city and the Miami River. Production ceased in 1993, and the site is being prepared for potential alternative use. Part of that preparation is the cleanup of environmental contaminants at the site. One of the contaminants is plutonium.

In 1969 a rupture occurred in an underground pipeline, releasing waste from a plutonium processing facility on the bluff above the flood plain of the Miami River. An abandoned stretch of the nineteenth-century Miami-Erie barge canal runs along the base of the slope outside the boundary of the plant. The canal is normally dry. Under periods of intense or prolonged rain, water collects in the canal and drains, through a ditch south of the Mound plant, into the Miami River. Excavation of soil near the rupture began January 24, 1969, and repairs on the pipeline were completed on January 26. On January 28 heavy rain began and continued through the 31st. Cleanup resumed in February, and additional soil near the rupture was removed. In April of 1969, the excavated areas were filled with uncontaminated soil.

In 1971 routine environmental sampling both on and off site suggested that plutonium had been dispersed into the environment. In 1975 a study of more than 1700 samples from sediment, biota, water, air, and soil indicated that a 1-mile section of the abandoned canal was contaminated. About 90 additional samples were collected in 1992 and 1993, confirming the general distribution of plutonium observed in the 1975 study.

This is a description of "where" on a large scale. One thing we will need to determine is whether or not this description is adequate.

Who: The U. S. Department of Energy; the City of Miamisburg; the Ohio EPA Office of Federal Facilities Oversight; the U. S. Environmental Protection Agency, Region V; and the Mound Action Committee

The Department of Energy is obligated to pay for the cleanup of the canal. The City of Miamisburg owns the land. The Ohio EPA Office of Federal Facilities Oversight has responsibility for direct regulatory oversight. The U. S. EPA oversees the Ohio EPA. The Mound Action Committee represents, in part, the local community. The criteria for remediation of the Canal must be agreed to by all these parties. The plans for meeting the criteria must be agreed to by all the parties. The criteria for determining whether the remediation criteria have been met must be agreed to by all the parties. The plan for meeting the criteria that determine whether the remediation criteria have been met must be agreed to by all the parties. Last, but not least, all the parties must, in the end, agree that the plan for meeting the criteria that determine the success of the remediation was executed in good faith and to every party's satisfaction.

SmartSampling is a process that requires explicit decision rules. For example, what exactly and unambiguously determines whether or not a discrete piece of ground is contaminated or uncontaminated? All the parties must agree to the rules unless one entity has been granted unilateral power. In the case of the Miami-Erie Canal, the consensus of a number of stakeholders is required.

What: Plutonium

But not all the plutonium will be removed. For many environmental contaminants, criteria are set that define allowable concentration levels in soil, water, or air. In the case of the Miami-Erie Canal the criteria for remediation are expressed in terms of the likelihood of exceeding 75 and 150 picocuries per gram (pCi/g) of plutonium. For example, one of the rules for the canal is that all soil will be removed where the probability of exceeding 75 pCi/g is greater than or equal to 0.05 (5%).

Note that the rule is explicitly probabilistic. The rule *does not say* "clean up to an average of 75 pCi/g" or "clean down to 75 pCi/g". What appears to complicate matters of compliance even further is a second criterion that can be stated as "all soil will be removed where the probability of exceeding 150 pCi/g is greater than zero".

We can now define our problem:

The Department of Energy is required to remediate a section of the Miami-Erie Canal adjacent to its former weapon-production plant to the satisfaction of the Ohio EPA Office of Federal Facilities Oversight, the U.S. EPA Region V, and local citizens. Satisfaction is achieved when the Department of Energy demonstrates that no soil remains where the probability of exceeding a concentration level of 75 pCi/g of plutonium is greater than or equal to 0.05 and that no soil remains where the probability of exceeding 150 pCi/g is greater than 0.0.

We will also assume that the Department of Energy would like to solve the problem we have just defined at the lowest possible cost.

To solve our problem we need to answer 4 questions.

Where do I send the bulldozer?

The intuitively obvious answer to the Department of Energy's problem is that a bulldozer, or in the case of Mound a backhoe, removes soil that is contaminated with plutonium. As we shall see, when one is standing in the Canal with limited data, uncertainties in the distribution of the contaminant, and compliance criteria that are explicitly probabilistic, where to send the bulldozer is anything but intuitively obvious.

How much confidence do I have in my decision?

The backhoe driver has gone home for the day. Based on your instructions, some soil was excavated and some soil was left in place. How much confidence do you have that the regulatory compliance criteria have been met?

What are the consequences if I make a mistake?
Despite your best efforts and professional judgment, mistakes are bound to happen. What are the consequences if some of the soil you left in place is contaminated? What are the consequences if some of the soil you just excavated for shipment to Utah is un-contaminated?

Have the stakeholder and regulatory concerns been addressed?
You have just spent several million dollars to excavate and ship several thousand cubic yards of silt loam from Ohio to a hole in the ground in Utah. How much of the plutonium went with it? How much remains? How is the remainder dispersed? What are the risks associated with the remainder? One assumes that the purpose of the exercise was to remove the plutonium. Has that really been accomplished?

These four questions are generic to any site where there is a possible contaminant, a performance criterion must be met if the contaminant is detected, and cost or technical feasibility is a constraint. Therefore, the process we will follow in this tutorial to answer these questions, the process we call SmartSampling, is generic to any site.

Building an Economic Objective Function

In this section we re-state the problem we are trying to solve in economic terms. The total cost of environmental remediation can be written in terms of three component costs: the cost of characterizing a site, the cost of treatment or removal of the contaminants, and the costs associated with design failure. We can express this in mathematical form as

Total Cost = Characterization Cost + Treatment Cost + Failure Cost

The last term in the equation is called the economic risk term. Under most circumstances we want to evaluate the economic objective function for a number of different design alternatives. What we are looking for is the least-cost solution to an environmental remediation.

The economic objective function for Mound is even simpler. At Mound, the cost of characterization is fixed. There is an on-site sample laboratory at the Canal. The laboratory is staffed and equipped. As a result, the cost of characterization is not a factor in evaluating alternative design strategies. Therefore, the economic objective function for the remediation of the Miami-Erie Canal can be written as

Total Cost = Treatment Cost + Failure Cost

We can now state our problem as “minimize the total cost of meeting the regulatory compliance criteria at the Miami-Erie Canal to the satisfaction of the regulatory and local community.”

As we shall see, Total Cost is a non-linear function of the two remaining terms in the equation. What appears to be a very simple statement of the problem has no simple solution.

Understanding the Economic Risk Term

The last term in our economic objective function is the product of two components: a probability of failure and a cost of failure.

Failure Cost = Probability of Failure x Cost of Failure

This is the risk component of our economic model. By including this term in our model and stating failure costs as a function of the likelihood of an error or mistake on our part, we do several important things. First, we explicitly acknowledge that there is uncertainty in our decision making. Second, we provide a framework for quantifying the level of uncertainty and the potential consequences. Third, we quantify what additional data is worth to us and compare that to the cost of additional data.

Let us first consider the cost of failure in the context of our environmental remediation. There are two different types of failure:

1. **The failure to remove a contaminated section of soil**
2. **The removal of an uncontaminated section of soil**

The first failure is a failure to meet regulatory compliance criteria and has an expected cost associated with it. The second failure is of no concern to the regulator but constitutes a design failure from the site's point of view and has an expected cost associated with it.

The likelihood of either type of failure is a function of the information available to us about a site. In other words, all our sampling and characterization at a site is expressed as the probability of failing to meet a design criterion.

Before going on to the section on characterization, we will rewrite our economic objective function for Mound with the expanded economic risk term in the equation.

Total Cost = Treatment Cost + (Probability of Failure x Cost of Failure)

Characterization and Sampling

One of the first questions we need to address is whether or not additional sampling of the canal is required; that is, do we already have enough information to start excavation? As we discussed in the section Problem Definition, the Department of Energy took numerous samples over a period of 24 years. In a review of sample data taken from the canal in 1992 and 1993, we came to the following conclusions:

> **The sample analysis techniques in use at that time generated uniform concentration values below 50 pCi/g. This suggests a high degree of inaccuracy.**
>
> **Very few samples were obtained in the critical range, between 50 and 200 pCi/g, for determining compliance.**
>
> **Verification samples taken during the same period did not correlate well with the site's soil-screening techniques; which constitute the majority of the data.**
>
> **Sampling conducted prior to the removal action provides only a gross picture of the nature and extent of the plutonium contamination.**

If cost were no object, the site could excavate well beyond and below the boundaries of the canal. Since cost was an object, the site had developed a baseline excavation plan based on the existing sample data. The site felt that the baseline plan was conservative; that is, the site would remove more soil than was necessary to meet the compliance criteria. The regulators were not completely convinced. Neither side had good data available to defend its arguments. It was clear that both sides, the site and the regulator, were working together in good faith. It was also clear that both sides were having difficulty interpreting the probabilistic compliance criteria using traditional deterministic methods.

At this point, DOE and the regulators authorized a demonstration of SmartSampling on three sections of the canal. In total, the canal removal action has been divided into 150 sections, with each section measuring 60 ft in width and 50 ft in length. The regulators and the site chose sections N23, N24, and N25 for the demonstration. These sections were picked because the site and regulators believed that contamination here might extend below the 4 ft predicted in the baseline excavation plan. Sampling and excavation were to proceed in stages:

- **A new round of sampling on the surface of the canal and excavation to a depth of 2 ft in all areas exceeding the compliance criteria.**
- **Sampling of the excavated surface and excavation to a depth of an additional 2 ft in all areas exceeding the compliance criteria.**
- **Prediction of contamination with depth based on the data from the sampling of the two surfaces above and excavation of all areas exceeding the compliance criteria below a depth of 4 ft.**

SmartSampling, as a process, is designed to be iterative. That is, samples are taken a few at a time, the information is analyzed, the economic objective function is updated, and a decision to take more samples is based on what the function predicts those samples are worth towards minimizing the total cost of the remediation.

The decision was made at Mound to over-sample the surface of the canal and the excavated surface below. There were three reasons for this decision. One was technical, one was political, and one was economic.

The technical reason is suggested by the review of the site's prior attempt to characterize the nature and extent of contamination in the canal. The site was planning to use their on-site rapid screening techniques to characterize the boundaries of their excavation for compliance and to make real-time dig or no-dig decisions. Their alternative was to send samples off site for analysis - a time consuming and costly process.

The initial sample plan was designed to achieve two goals. The first was to obtain enough samples in the critical range of 50 to 200 pCi/g to compare the site's rapid-screening procedures with off-site analysis.

The intent was to take enough samples so that at least 60 of the samples fell into the critical range. Those samples would be split, with one portion sent to the rapid-screening lab and one portion sent off-site for analysis. The second goal was to obtain enough samples so that a reasonably precise map of the areas requiring excavation could be generated the first time through. This second goal was driven by political considerations. The site was under great pressure to "move the dirt." Spring rains in Ohio delayed the start of some activities. The mayor of Miamisburg was a frequent visitor.

The economic reasons to obtain as many samples as possible the first time through are simple. The project was able to demonstrate that the on-site rapid-screening samples provide defensible numbers. There is a fixed cost associated with the on-site lab. Whether they take one sample a day or 100, the fixed cost remains the same. Therefore, the cost per sample decreases as the number of samples increases up to the full capacity of the lab. There is no economic incentive to minimize the number of samples under the circumstances at this site. Later, when we come to the section Evaluating Economic Trade-Offs, the worth of additional sampling at this site will become clear.

At this point we want to review the reasons for sampling. The data available from the site do not provide the *information* needed to answer the four questions posed earlier:

> **Where do I send the bulldozer?**
> **How much confidence do I have in my decision?**
> **What are the consequences if I make a mistake?**
> **Have the stakeholder and regulatory concerns been addressed?**

If these questions can be answered, then the following problem can be solved: *the Department of Energy is required to remediate a section of the Miami-Erie Canal adjacent to their former weapon production plant to the satisfaction of the Ohio EPA Office of Federal Facilities Oversight, the U.S. EPA Region V, and local citizens. Satisfaction will be achieved if the Department of Energy can demonstrate that no soil remains where the probability of exceeding a concentration level of 75 pCi/g of plutonium is greater than or equal to 0.05 and that no soil remains where the probability of exceeding 150 pCi/g is greater than 0.0.*

Figure 1 is a plan view of the sample locations on the surface of the canal under SmartSampling. The size of the black dots corresponds to plutonium concentration. The bigger the dot, the greater the measured concentration of plutonium. Under the agreement negotiated between the Department of Energy and the stakeholders, 25 samples on ten-foot spacing are to be taken in each section of the canal. The locations are defined by 50 ft x 50 ft grids sectioned every ten ft. The origin of each grid in each section is determined by random number so that as one crosses from section to section the grids are offset. SmartSampling added eight nested grids on a smaller spacing. In total, 152 samples were taken from the surface of the canal.

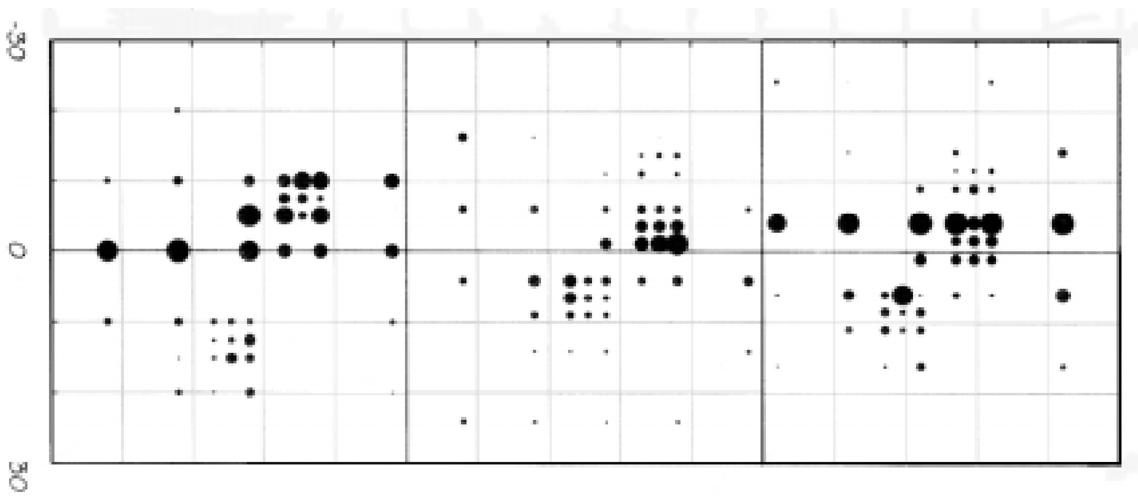


Figure 1

The nested grids provide information that will be used in a geostatistical analysis of the sample data. Geostatistics, unlike statistics, assumes that the relationship between two measurements of plutonium spaced near each other is stronger than the relationship between two measurements taken far away from each other. The design of a sample pattern and the analysis of the sample data is different in geostatistics than statistics. When the data do not support this relationship, the problem degrades to a classical statistical problem.

Once the samples were taken, the surface was excavated to depth of two feet, and a similar sample pattern was laid out on the exposed surface and samples taken.

At this point reality intruded to change the design of the SmartSampling plan. The exposed surface, 2 ft below the original soil surface of the canal, was virtually uncontaminated. Remember, these three sections were chosen because of concerns that contamination might exist below a depth of 4 ft. The idea that contaminants may not be dispersed exactly as predicted in a baseline assessment should come as no surprise. Although the project had plans to use data from at least two contaminated surfaces and possibly three to support the analyses to follow characterization, data only from the surface of the canal will be used.

Samples have now been taken. Next, specific questions about the data will be asked to determine if we have the information needed to answer the questions raised. Note the distinction being made between data and information. It is easy to collect data. *It is hard to obtain information*.

The first question is "how are the individual measurements of plutonium concentration distributed?" The answer is illustrated in figure 2. Figure 2 is a histogram. It displays the percentage of the 152 measured values that fall into discrete little packages. For example, almost half the samples had plutonium concentrations less than or equal to 33 pCi/g. Three quarters of all the samples had concentrations less than 100 pCi/g. Only a small percentage of the samples exceeded 200 pCi/g.

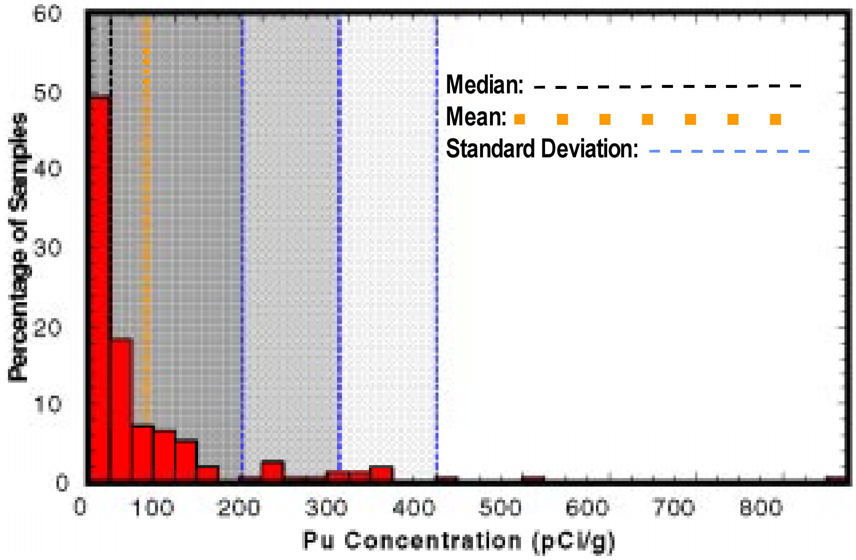
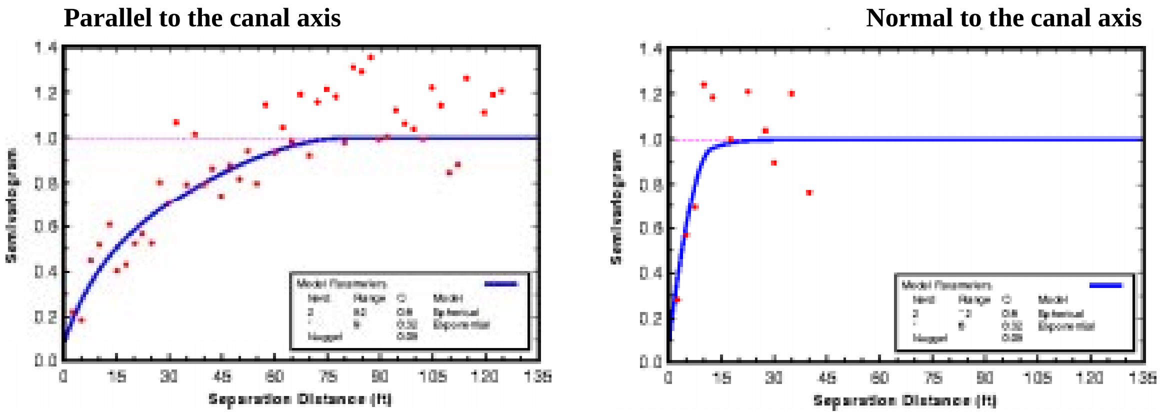


Figure 2

There is additional information in Figure 2. Notice the shape of the histogram: many low values decreasing exponentially to a few high values. This exponential shape is important. First, it illustrates why the mean or average value of the distribution is a poor predictor of what one would expect to see if another sample were to be taken. Note that the mean value of about 100 pCi/g is much higher than the median value of about 33 pCi/g (half the number of samples are less than, and half the number of samples are greater than 33 pCi/g). Second, it states that high values are not unexpected and should not be a surprise when they occur.

The next question is whether the measured values of plutonium are related to each other in space. This is a geostatistical question and the answer is provided in a figure called a variogram. The variogram for our canal data is illustrated in Figure 3.



a.) b.)

Figure 3

The variogram plots variance (differences between pairs of samples) versus increasing distance between samples. If there is a spatial relationship, the variance decreases as the distance between sample pairs decreases. Both illustrations in Figure 3 are informative. In Figure 3a we have asked if there is spatial correlation between sample values down the long axis of the canal in the 3 sections where we sampled. In Figure 3b we have asked if there is spatial correlation between sample values as we traverse the width of the canal. In both cases the answer is yes. The differences between pairs decreases as the pairs get closer together. In a comparison of the two figures, there is a striking difference. The range, the distance over which a sample provides some information about the value of another sample, is much longer down the axis of the canal than across the width of the canal.

This difference is called anisotropy and is a common property of many geotechnical phenomena.

When it comes time to model the distribution of plutonium in the canal and the likelihood of meeting the compliance criteria, the information in the histogram and the variogram will be used to condition and constrain the model.

All the data and information needed to generate a map, Figure 4, of expected plutonium concentrations on the surface of the canal is now available. High values of concentration are red. Low values are blue. The map shows high values of plutonium down the center of the canal.

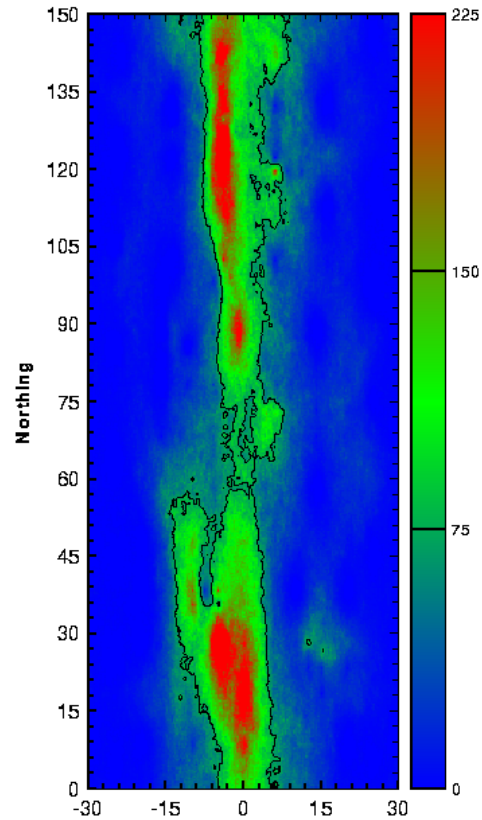


Figure 4

Mapping the expected value of the distribution of a contaminant is where most sites end their analyses. As you shall see in a moment, very little information here is relevant to the problem as defined or to the questions posed. The map does provide some comforting information. Higher levels of contamination are primarily confined to the center of the canal. This is consistent with the mode of deposition, plutonium contaminated waste water flooding what is, for all practical purposes, a ditch. There is a fairly broad range of concentration values down the center of the canal. This variation could be the result of the original depositional event in 1969, or it could be the result of reworking of sediment over the past 28 years.

When it rains, the canal floods. There is a shallow gradient to a ditch that drains into the Miami River. Over the past 28 years, it has rained many times in Ohio. There can be standing water in the canal for prolonged periods of time.

The somewhat splotchy distribution of contaminant values as one approaches the edges of the map probably represent man-made disturbances and re-working of the plutonium. Over the years there has been some dredging of the canal, evidenced by obvious spoils piles along the banks in some areas. The canal has also been used as a dumping ground for tires, empty anti-freeze containers, and assorted other cultural artifacts.

Another comfort is the elevated levels of plutonium on the surface. This supports the site's contention that the plutonium has bound to the sediment in the canal and is reasonably immobile. The abrupt lack of plutonium 2 ft below the surface also supports this argument.

The real issue is whether generating a model and a map of expected values of plutonium provides the answers to the questions that have been asked.

The first question we want to answer is, "where do we send the bulldozer?"

We know from our statement of the problem that we need to remove any soil where the probability of exceeding a concentration level of 75 pCi/g is greater than or equal to 0.05 and the probability of exceeding 150 pCi/g is greater than 0.0. Figure 4 does not tell us where to dig.

An analysis of expected values does not provide the answer to the 3 remaining questions either: how much confidence do I have in my decision? What are the consequences if I am wrong? Have the stakeholder and regulatory concerns been addressed?

In the next section, Quantifying Geologic Uncertainty, we will take the information in the histogram, the variogram, and the samples and generate the models we need to answer the questions and evaluate the economic objective function.

Smart Sampling

Quantifying Geologic Uncertainty

Imagine yourself standing in the canal. Imagine a backhoe. At the 152 locations where you have taken a sample you know with perfect certainty, for all practical purposes, whether or not the backhoe operator should remove the soil. If the concentration of plutonium in the sample was greater than or equal to 75 pCi/g, the soil is removed. If the concentration is less than 75 pCi/g, the soil stays. Now, what are you going to tell the operator to do at all the other locations?

As soon as you step away from a sampled location there is uncertainty about the plutonium concentration. The regulators and the stakeholders understand this. That is why the compliance criteria have been written in terms of the likelihood of exceeding 75 and 150 pCi/g.

It might be worthwhile at this point to consider how much of the site we interrogated by taking 152 samples. Each sample we took had a diameter of 0.33 feet. There are 81 potential non-overlapping sample locations in every square yard of soil (Figure 5). The area we are sampling is 20 yards wide and 50 yards long. There are 81,000 potential sample locations at our site.

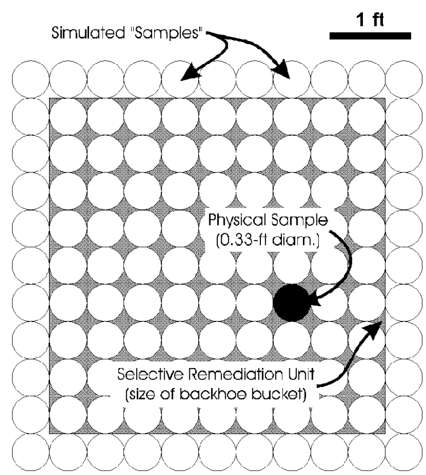


Figure 5

Now ask yourself the following question. Can I predict the likelihood of exceeding the compliance criteria at all these unsampled locations given the information currently available to me? Because if I can, then I know precisely where to dig to meet the compliance criteria.

Yes, you can predict the likelihood. The process you are going to use is called geostatistical simulation. Not too many years ago, this process

would have required a supercomputer. Today it can be performed on a notebook computer in the field.

The process we are going to execute and follow is outlined in Figure 6. We are going to use the histogram, the sample values and locations, and the variogram to generate 100 separate models of the concentration of plutonium at the canal. Each of the models will preserve the measured value of plutonium at the location it was sampled, the statistical properties of the original sample data, and the spatial correlation of the original data. Each model will be a plausible and equally likely representation of what might be happening at all the locations where we have not sampled.

Some readers will instantly recognize what we have just done as a variation of what is called a Monte Carlo process. Instead of generating multiple, equally likely representations of a univariate process, we are now generating multiple, equally likely representations of a geometric process. The process is exactly the same for a 3-dimensional problem. The software to execute this type of simulation is available in the public domain and can be accessed through the Related Web Sites.

When we are finished with the simulation, we will have 100 realizations of what could occur at each of the 80,848 locations *where we did not take a sample.* What that means is that, at each location, we can summarize the 100 values as a histogram. The histogram at each location tells us how likely we would be to draw certain values of plutonium, as a function of the information currently available to us, *if* we were to take a sample in that location. Of immediate concern to us is that we can now determine the locations at the site where the probability of exceeding a plutonium concentration of 75 pCi/g is greater than or equal to 0.05.

If we take the average of the 100 realizations at each location and map them, we would get the map of expected concentration in Figure 4.

Since we do not want to give the backhoe operator 100 maps and tell him to figure out where to excavate, we need to summarize the simulation results in a form that is easy to interpret.

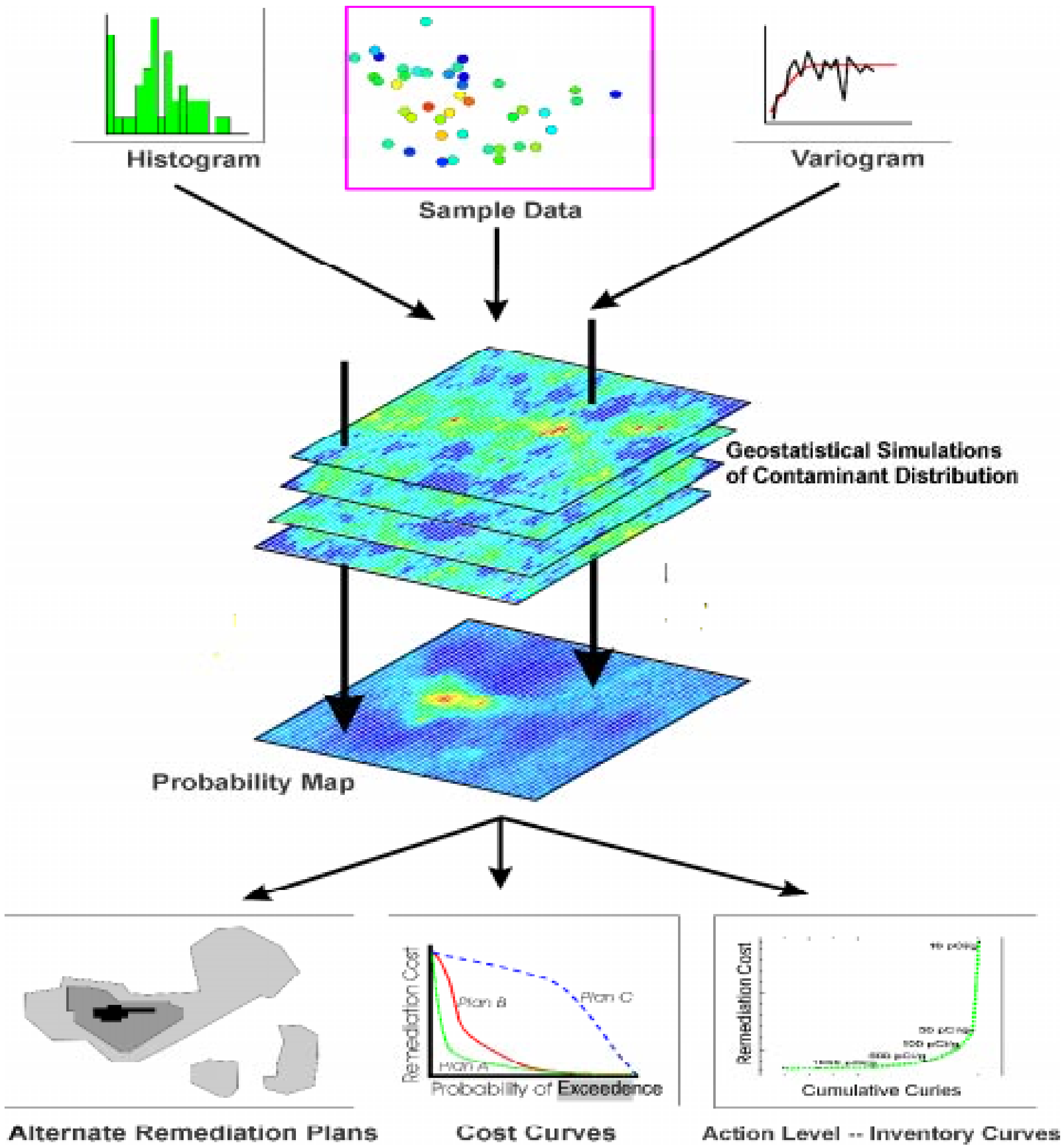
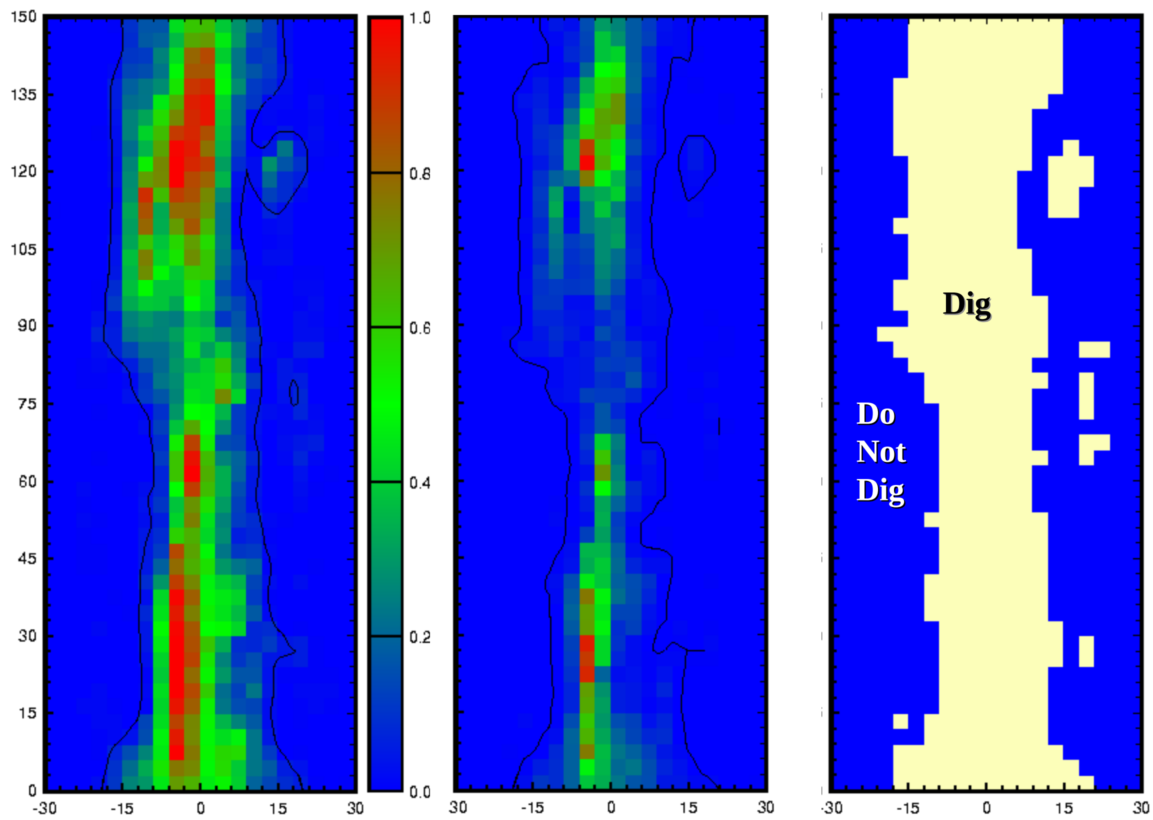

Histogram
Sample Data
Variogram
Geostatistical Simulations
of Contaminant Distribution
Probability Map
Remediation Cost
Plan B
Plan C
Plan A
Probability of Exceedence
Remediation Cost
Cumulative Curies
Alternate Remediation Plans
Cost Curves
Action Level -- Inventory Curves

Figure 6

The summary information will take a number of forms. We want to use the results of the simulation to answer the questions we have asked because those answers provide the solution to the problem we have posed.

We will start by summarizing the information we need to answer the question of where to send the bulldozer. Figure 7 illustrates the process of generating a remediation map, a map that identifies exactly what patches of ground are going to removed in order to meet the compliance criteria.



a.) b.) c.)

Figure 7

There are 3 illustrations in Figure 7. Figure 7a and 7b are probability maps. The values of the color scale are probabilities that range from 0 to 1.0. Figure 7a is a map of the probability that the average plutonium concentration in any 3 ft x 3 ft section of the canal exceeds 75 pCi/g. The dashed line in Figure 7a defines the 0.05 probability contour. Figure 7b is a map of the probability that the average plutonium

concentration in any 3 ft x 3 ft section of the canal exceeds 150 pCi/g. The dashed line in Figure 7b defines the 0.01 probability contour. Figure 7c is the actual remediation map. It tells the backhoe operator exactly where to excavate in order to meet both compliance criteria.

Two very important but very subtle things just occurred in the preceding paragraph and we need to discuss each one.

First, we mapped the average probability of exceeding the compliance criteria over a 3 ft x 3 ft piece of ground. There is a practical reason for summarizing the simulation results at this scale: 3 ft x 3 ft is the size of the backhoe blade. It is the smallest piece of ground that can be removed. The average of a piece of ground this size is not well represented by a single sample that is only 4" across, as we discussed earlier. To obtain a robust average we have done two things. We took a number of closely spaced samples, the nested grids, to obtain a measure of local variability, and we conducted the computer simulation at the same scale as the measurements to preserve the statistics of the measured data. To obtain the average concentration over the 3 ft x 3 ft section, we take the average of the 8,100 concentration values generated in that section in the simulation.

Second, we chose as our remediation contour for 150 pCi/g a value of 0.01 and not 0.0. This is a simple consequence of the laws of probability. The concept of certainty, a probability of either 0.0 or 1.0, an event either did not occur or it did, applies only after an experiment has been conducted - in this case, the sample taken. Absent a sample, the probability that the concentration at any location will exceed 150 pCi/g must be a number between, but not equal to, 0.0 and 1.0. Strict, unyielding adherence to the compliance criterion for 150 pCi/g requires that the site either take 81,000 samples in the three sections under discussion or simply excavate all the soil. How we deal with the consequences of these decisions is discussed in the section Evaluating Economic Trade-Offs.

An important point to note here is that the problems we have been discussing are not unique to Mound. In fact they are not unique. Measurements are not taken at the scale of a bulldozer blade, and the problem of relating what you measure to what you do exists

everywhere. The problem that strict adherence to compliance criteria may not be technically, physically, or economically feasible (or all three) does not mean that the criteria were set in bad faith or that the fundamental objectives of the remedial activity can not be achieved.

We have just explicitly answered the first of the four questions we needed to answer. With our remediation map we can give precise and unambiguous directions to the backhoe operator.

We have three more questions to answer: How much confidence do I have in those instructions? What are the consequences if those instructions were wrong? To what extent did my actions address the stakeholder and regulatory concerns? We are going to pose these as economic questions in the next section and use the cost-objective function, the cost data from the site, and the results of our uncertainty analysis to propose an answer.

Evaluating Economic Trade-Offs

We are going to start by considering the consequences of our actions: an action, in the context of the problem we are solving, is the removal or leaving in place of a section of soil 3 ft square and 1.5 ft deep. An action can also be the decision to obtain more samples in order to refine the excavation plan. The setting of a compliance criterion is also an action. The consequence of those actions is an impact on the total cost of the removal action. To understand the consequences of our actions we need to understand the trade-offs between characterization and sampling costs, removal and shipment costs, the costs we might be forced to pay for a failure to meet the compliance criteria, and the costs of an overly conservative excavation.

We have just defined the consequences of our actions in terms of dollars. Every decision we make is going to have a direct or potential economic effect on the total cost of the removal action. This relationship is expressed in the economic objective function we developed. To understand the consequences of our decisions we need to understand how this function behaves at this site.

Total Cost = Treatment Cost + (Probability of Failure x Cost of Failure)

How this function behaves is going to be a function of the information available to us about the distribution of plutonium at the site, the site specific costs, and the uncertainties we have about data.

At this point, you may want to review the discussion in Building an Economic Objective Function and Understanding the Economic Risk Term.

Table 1 is summary of the cost information, originally provided by the site, needed to calculate the value of the economic objective function.

Table 1 - Economic Data	Cost ($)
Panel size (selective remediation unit): 3 ft x 3 ft x 1.5 ft avg. depth = 13.5 ft^3	**--**
Remediation cost, initial, per ft^3 of soil: $2.91 transp. + $0.24 car liner + $6.60 disposal + $1.48 operations & management	**11.23**
Re-remediation cost (upon failure), per ft^3 of soil (Pu activity < 150 pCi/g): Cost factor x 2	**22.46**
Re-remediation cost (upon failure), per ft^3 of soil (Pu activity > 150 pCi/g): Cost factor x 5	**56.15**
Base-case excavation volume: based on cross-section profile of canal segment N-24, 64 ft^2 x 150 ft = 9600 ft^3 x $11.23/ft^3	**107,808**

Figure 8 is the total cost-objective function for the 3 sections we sampled at the canal using the original cost data in Table 1. The figure plots the total cost, removal cost, and failure cost versus the probability of failing to meet the regulatory compliance criteria. The purple line is the site's cost to execute the removal action as described in their baseline plan.

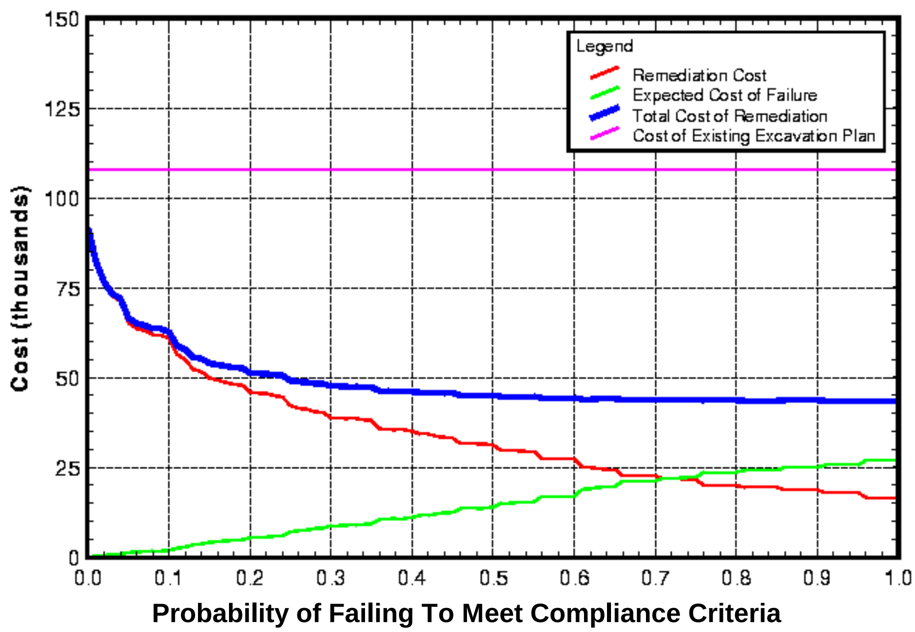


Figure 8

We can now give quantitative meaning to the concepts of confidence and consequence. The vertical axis of Figure 8 is consequence, the horizontal is confidence. Consider what the horizontal axis is telling us. At the far left-hand side, at 0.0, the value of the total cost is at its

maximum. The function is telling you what the total cost will be if you want to execute the removal action with no likelihood of exceeding the regulatory compliance criteria. You will have a very high degree of confidence that the compliance criteria will be met and, as a consequence, the removal action will cost you about $90,000. Consider the far right-hand side of the horizontal axis, the 1.0. Here you have decided you will only remediate those sections of the canal where you know with absolute certainty you exceed the compliance criteria. These are only the sections where the concentration of plutonium in one of the 152 samples was greater than or equal to 75 pCi/g. With the information obtained from the site data, you will know, again with a very high degree of confidence, that many other sections of the site exceed the compliance criteria. You also know, with a high degree of confidence (the green line) that the regulator will detect some, if not all, your mistakes. According to the figure, as a consequence of this last decision, the total cost of the removal action will be reduced by almost half!

We will discuss shortly whether or not the site's failure costs are realistic.

In summary, Figure 8 is telling us that, if we are willing to risk the probability of a failure to excavate a panel that exceeds the compliance criteria, our removal costs will drop (the red line) as we increase that risk, our penalty for failure costs will go up (the green), and our total cost (the blue line) will continue to decrease. It is also telling us that, regardless of what we do, as a result of taking more samples and performing the geostatistical simulation, all our current alternatives are cheaper than what we were proposing to do in the baseline plan.

Figure 8 is a model of the consequences of decisions made by rational people. The purpose of a decision model is to help those people evaluate whether or not the consequences of those decisions are rational. The model in Figure 8 was reviewed by the U. S. Department of Energy, the Ohio EPA, and the U. S. EPA. The Ohio EPA made it clear that the site had underestimated penalties should the State encounter a substantial number of verification samples in excess of the regulatory compliance criteria. Discussions between the Ohio EPA and the Department of Energy resulted in the following revisions to the original assumptions:

- **Should the Ohio EPA, upon verification of the site's remediation, find a substantial number of samples in excess of the regulatory compliance criteria there would be a serious loss of confidence in the site's ability to meet negotiated compliance criteria.**
- **That loss of confidence would occur somewhere around a point where 25 out of every 100 verification samples were in excess of the compliance criteria.**
- **The loss of confidence would result in delays, changes in reporting requirements, and a substantial increase in cost to the site.**

Since there were no explicit decision criteria set for assigning the amount of penalty, the objective function was reevaluated as a function of increasing penalty costs. Figure 9 is an illustration of the revised objective function. The function is now displayed as a penalty surface in three dimensions and only the total restoration cost is displayed.

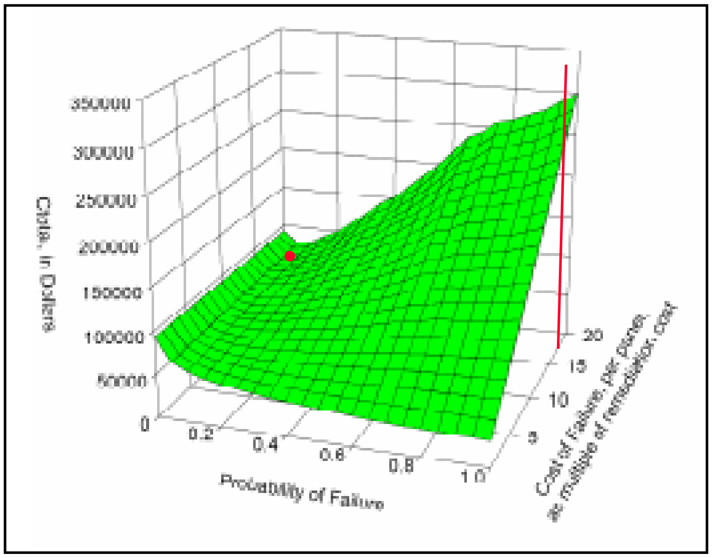


Figure 9

Like the function in Figure 8, cost is plotted on the vertical axis versus the probability of failing to meet the compliance criteria, the Probability of Failure, on the horizontal axis. In Figure 9 there is a third axis labeled the Cost of Failure, per panel, as a multiple of remediation cost. As economic penalties increase in direct proportion to the cost of remediation, the economic incentive to err decreases. The new function allows us to ask and answer questions that are important

to both the regulator and the site. For the regulator, the function answers the question "how large do penalties need to be to provide an economic incentive to comply with the compliance criteria while still providing the site the opportunity to make honest errors without fear of punitive economic penalties?" The regulator has stated that a loss of confidence would occur at a point where 25 out of 100 verification samples exceed the compliance criteria. There is a point on the function where the expected cost of a probability of failure of 0.25 is greater than the original baseline cost. That point is reached once the penalty cost reaches a multiple of 18 times the cost of remediation and is illustrated by the red line in Figure 9.

The site would like to know if, given the current sample data, there is an opportunity to minimize the cost of the remediation despite the higher penalty. As in the original objective function, perfection does not appear to be cost effective. It clearly pays the site to assume some risk, on the order of 10%, in the classification of the panels as clean or dirty. The site's best option is illustrated by the red dot in Figure 9.

The substantial increase in cost that the Department of Energy believes it would incur as a result of the Ohio EPA's loss of confidence in the Department's ability to remediate the Canal is well in excess of 18 times cost.

The sampling and analysis conducted to this point have provided us with explicit answers to the first 3 questions we posed: where do we send the bulldozer? How much confidence do we have that the compliance criteria have been met? What are consequences if they have not? But we have yet to adequately answer the question posed as, have the stakeholder and regulatory concerns been addressed? The answer to that question is shown in Figure 10.

The site, the regulators, and the community usually assume that if the compliance criteria for concentration limits have been met, the problem has been solved. The relationship between inventory and concentration limit is a non-linear function and is site specific. SmartSampling assumes that the purpose of the excavation is to remove the contaminant since that was what all the fuss was about in the first place. This is a classic concept in geostatistics. Geostatistics evolved as

discipline over forty years ago in the mining industry. A mining company wants to extract as much ore as possible at the cheapest possible price.

Figure 10 is the inventory curve for the 3 sections we sampled at the canal. The inventory curve describes the amount of plutonium that is removed as a function of the number of 3 ft x 3 ft panels that are excavated. The vertical axis is labeled on the left in terms of increasing number of panels that are excavated and on the right as increasing cost. The horizontal axis is labeled as both the cumulative fraction of the plutonium that is removed and as the cumulative activity in Curies.

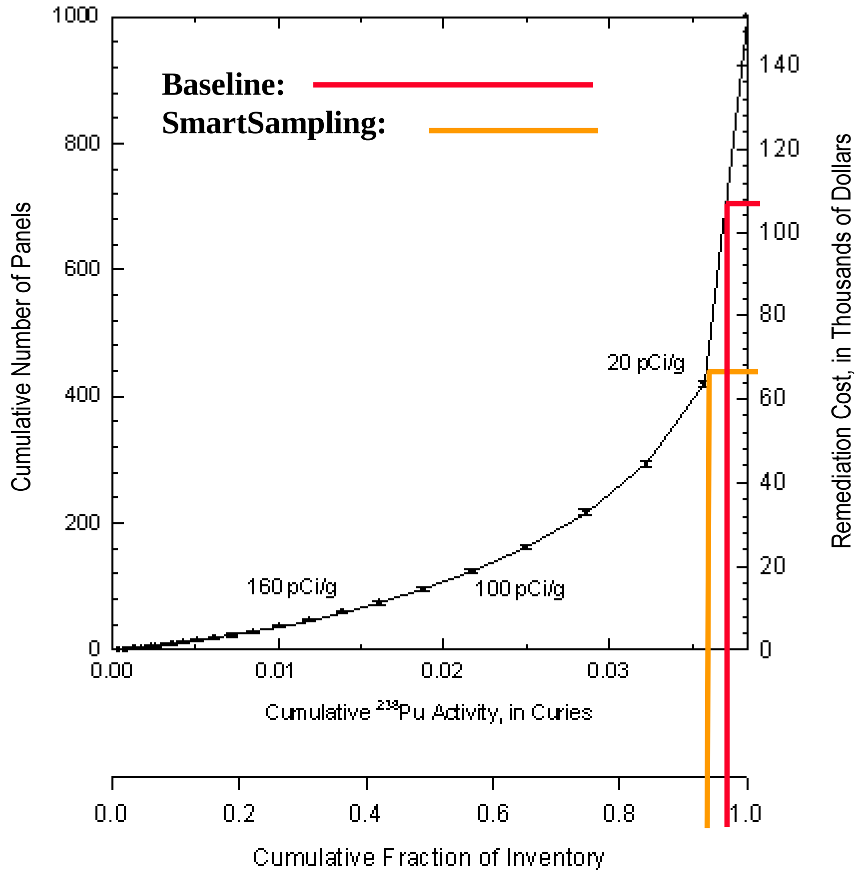


Figure 10

We could have generated this curve prior to performing the economic analysis. Had we done that, the information on the right hand side of

the vertical axis, remediation cost, would not be available to us. We can never forget that remediation is both an economic and a technical feasibility problem. If it were not, concentration limits for any and all contaminants would be set to zero.

The curve in Figure 10 is derived directly from the analysis of the site data. The points on the curve labeled 160, 100, and 20 pCi/g are predictions of the average concentration of plutonium in the soil that remains. The red line shows where the site's original remediation plan intersects the curve. The orange line is the remediation plan illustrated in Figure 7c. The inventory curve is important for several reasons. The curve provides the regulatory community and citizens with an estimate of how much plutonium will be removed and how much will remain under alternative design plans (the site's baseline plan for excavation and the excavation plan developed in this tutorial are two different alternative designs). The curve clearly illustrates the diminishing returns that would be achieved by additional excavation. The SmartSampling excavation plan removes about 95% of the plutonium at a cost of $67,000. The site's original excavation plan removes about 97% of the plutonium at a cost of $108,000.

The process is now complete.

Smart Sampling

Related Web Sites

Geostatistics & Software
Colorado School of Mines, http://uncert.mines.edu/
Stanford Center for Reservoir Forecasting,
http://ekofisk.stanford.edu/SCRF.html
AI-GEOSTATS, http://java.ei.jrc.it/rem/gregoire/
Environmental Modeling and System Analysis Laboratory, Russian Academy of Sciences, http://ibrae.ac.ru/~mkanev/index.html

SmartSampling
Sandia National Laboratories, http://www.nwer.sandia.gov/sample/

SmartSampling Sponsors
Innovative Treatment Remediation Demonstration,
http://www.em.doe.gov/itrd/
Subsurface Contaminants Focus Area
http://em-52.doe.gov/ifd/scfa.htm
Mound, http://www.doe-md.gov/

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